Development of PBS-Integrated Coherent Mixer Using Silica-Based Planar Lightwave Circuit

Takashi Inoue, Hiroshi Kawashima*, Noritaka Matsubara*, and Kazutaka Nara**

ABSTRACT A silica-based planar lightwave circuit (PLC) that is required for a receiver front-end used in digital coherent telecommunication system is developed by integrating a polarization-beam splitter (PBS) and a 90-degree hybrid mixer. At first, by configuring a PBS for signal with a double-pass Mach-Zehnder interferometer, a PBS-integrated coherent mixer chip is developed and a polarization extinction ratio (PER) higher than 30 dB is achieved. In the next stage, downsizing of a PLC chip is studied. For this purpose, the relative refractive index difference Δ is improved to 1.8%, and a circuit layout of folded waveguide is employed. As a result, an ultra-small PBS integrated mixer chip with dimension of 12 mm×12 mm is realized.
Using the developed chips in digital coherent receivers, experiments to demodulate dual-polarization quadrature phase-shift keying (DP-QPSK) signals at 40 Gbit/s and 100 Gbit/s are conducted, and excellent performances were confirmed in both cases.

1. INTRODUCTION

The polarization-multiplexed quadrature phase-shift keying transmission system combined with the digital signal processing shows great promise as the next-generation transmission system with the bit-rate higher than 100 Gbit/s in one channel. Especially, the DP-QPSK is recognized as a standard format in 100 Gbit/s Ethernet systems, and related specifications for transmitters and receivers are standardized in Optical Internetworking Forum (OIF) [3]. Among them, the specifications of an optical receiver front-end have been developed, which comprise a PBS, 90-degree hybrid mixers, balanced photo detectors (BPDs) and transimpedance amplifiers in a single module, and plays the roles of splitting the multiplexed polarizations , demodulating a phase-modulated optical signal, and converting the optical signal to the electrical one. In a front-end module, the PBS and the 90-degree hybrid mixers are required to be small so that they can be packaged in the specified size of the module. In addition, optical features such as low loss, high accuracy, and stability are desired for the devices. Finally, they should be capable of mass-production at low cost. To realize a product which satisfies these requirements, we investigated the development of the optical circuit which integrated the PBS and the 90-degree hybrid mixer in a planar lightwave circuit [4) ~ 6)]. This report shows the specific development results.

In Section 2, we propose a PLC integrating a PBS consisting of cascaded Mach-Zehnder interferometers (MZIs) and 90-degree hybrid mixers, where the polarization-extinction ratio for the dual-polarization optical signals is drastically improved.

Section 3 focuses on downsizing of a PBS-integrated coherent mixer chip, and shows a fabrication result of ultra-small PLC chip with the dimension of 12 mm ×12 mm. To downsize the chip dimension, we increase the Δ of a waveguide to 1.8% in the PLC fabricating process, and develop the circuit layout of folded waveguide configuration.

2. DEVELOPMENT OF THE DOUBLE-PASS PBS-INTEGRATED COHERENT MIXER

Both the stable operation and the downsizing are possible by applying a PLC to passive optical components such as PBS and 90-degree hybrid mixer. In fact, various experimental results are reported [7) ~ 9)]. Combining these technologies, a PLC which has a PBS and a 90-degree hybrid mixer integrated in one chip is proposed [10)]. Reference 10) reports that the PBS comprised of a single MZI has the PER of approximately 25 dB. In this section, for design of PBS-integrated coherent mixer, we propose to compose a PBS of a double-pass cascaded-type MZI to improve the PER of polarization-multiplexed optical signal [9)].

* Fitel Photonics Laboratory R&D Div.

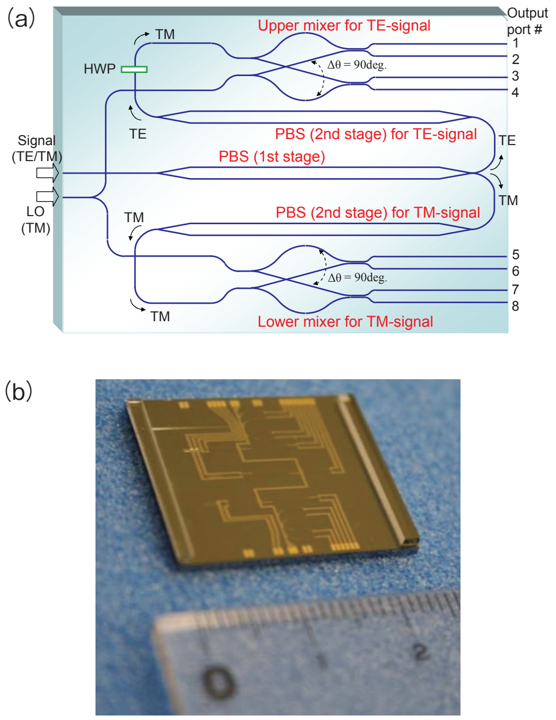


Figure 1 **(a) Schematic diagram of the proposed double-pass PBS-integrated coherent mixer based on PLC, and (b) picture of a fabricated PLC-chip.**

Figure 1(a) shows a schematic diagram of the circuit layout of the proposed PLC chip. The input signal propagates through the first stage PBS and the signal is split into the TE and the TM polarizations. The second stage PBS improves the PER of the TE/TM signals. We note in Figure 1(a) that the waveguides after the first- and second-stage double-pass Mach-Zehnder PBSs are folded, which contributes to a significant downsizing of the longitudinal dimension of the chip.

Between the second PBS and the mixer for the TE-signal, a half-wave plate (HWP) with 45-degree inclined principal axis is inserted. And then, the TE-signal of the optical signal is converted to the TM-mode and injected into the upper mixer of the chip. Meanwhile, the TM polarization component of the optical signal after propagating through the PBS is directly injected into the lower mixer of the chip without any polarization conversion.

On the other hand, the local oscillator (LO) with the TM polarization is injected into the PLC and guided to the upper and the lower 90-degree hybrid mixers after splitting. The split LOs interfere with the optical signals at upper and lower mixers and are emitted from the eight output ports of the PLC. The lights emitted from the PLC chip are injected into four BPDs through free-space optics or optical fibers.

Figure 1(b) shows a picture of the fabricated chip with the dimension of 25 mm×21 mm. The maximum insertion loss between the input port and the output port is 10.1 dB: this includes the 6 dB of the intrinsic loss of the 90-degree hybrid mixer and the bonding loss associated with the optical fibers used for the loss evaluation. In a similar way, the maximum insertion loss between LO and each output port is 11.6 dB: this includes the 3 dB of the intrinsic loss of the power splitter, 9 dB of the intrinsic loss of the 90-degree hybrid mixer and the bonding loss associated with the input and the output optical fibers. The minimum PER of the optical signal passes is 33.2 dB at 1.55 μm. An extremely large PER is obtained thanks to the double–pass cascaded-MZI structure for the PBS.

In order to evaluate the phase characteristics of a 90-degree hybrid mixer, we configure MZIs combining the mixer with an extra PLC chip consisting of a single input waveguide, a beam splitter, and two optical paths led to the output with different lengths. Note here that we adjust the path-length difference so that the MZIs have the sinusoidal interference pattern in the frequency domain with the free-spectral range (FSR) of 100 GHz. Figure 2 shows the "MZI intensity transfer function vs. the wavelength" of the upper and the lower mixers. From this measurement result, we confirm that the upper and lower mixers well operate as 90-degree optical hybrid mixers.

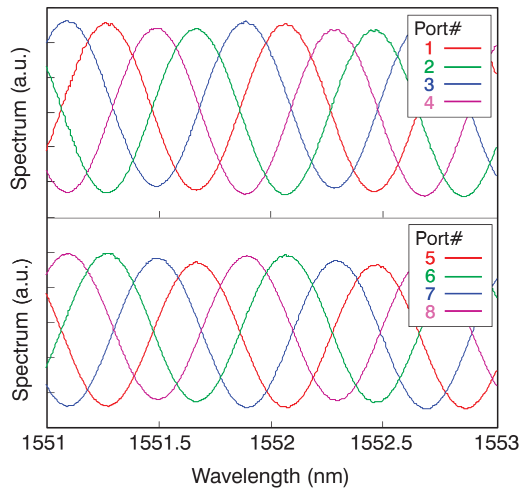


Figure 2 **The interference patterns of MZIs comprising the integrated coherent mixers.**

We conduct a transmission experiment of a 40-Gbit/s DP-QPSK signal using the fabricated PLC chip shown above in a digital coherent receiver. Figure 3 shows the experimental setup. The wavelength of the optical signal and the local oscillator was 1552 nm. A 200-km single mode fiber(SMF) was used for the transmission line. The developed double-pass PBS-integrated coherent mixer was allocated in front of the BPDs in the receiver, and optical fibers were used to connect the PLC and the BPDs. In this experiment, instead of using the HWP shown in Figure 1 (a), the input LO was adjusted to contain the same optical power for both of the TE/TM modes. In this case, the optical demodulation operation works well, though the optical loss for LO has been increased by 3 dB.

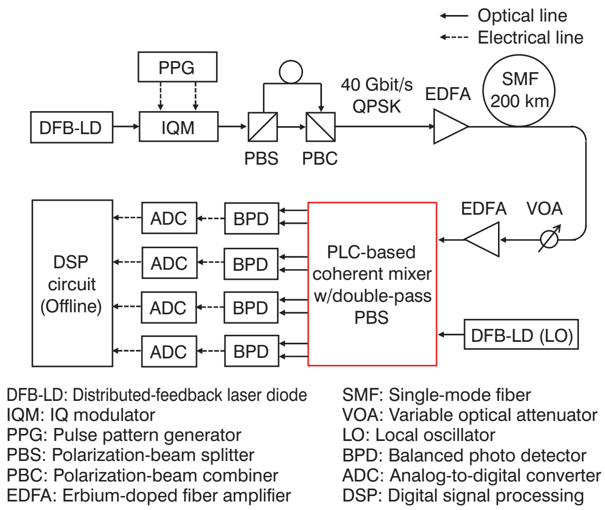


Figure 3 The setup for the 40-Gbit/s DP-QPSK signal transmission experiment.

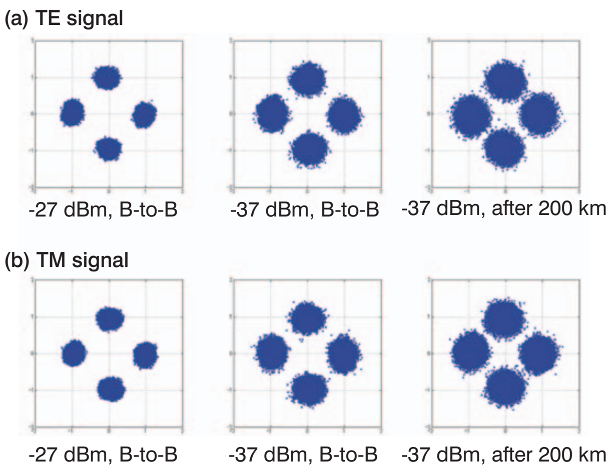


Figure 4 The constellation maps of back-to-back (B-to-B) and transmitted DP-QPSK signals.

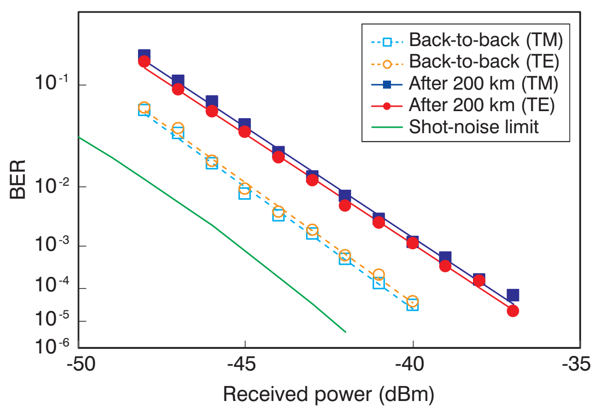


Figure 5 BER characteristics of 40-Gbit/s DP-QPSK signals.

Figure 4 shows the constellation maps of the received 40-Gbit/s DP-QPSK signals at back-to-back and after a 200-km transmission. In Figure 4, clear constellation maps are observed for both the TE/TM modes of the polarization-demultiplexed signal. Figure 5 shows the bit-error rate (BER) characteristics. The BER is observed even for the signal transmitted over the long distance, and the satisfactory performance of the developed PLC as a component in a coherent receiver is confirmed.

3. DEVELOPMENT OF AN ULTRA SMALL PBS-INTEGRATED COHERENT MIXER USING 1.8% Δ PROCESS

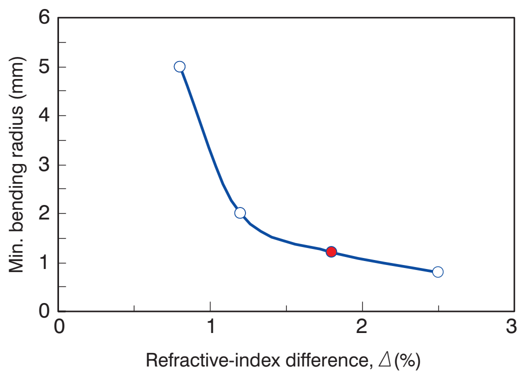
The chip dimension of the double-pass PBS-integrated coherent mixer which is reported in the previous section is 25 mm×21 mm. In consideration of the practical aspect, a more compact dimension is required. In particular, for use with enough room in the receiver front-end module standardized by OIF [11], a dimension of less than 15 mm square is desired.

In this section, development of a significant downsizing of the chip is investigated. For this purpose, we improve a PLC fabrication process with a higher Δ so that the bending radius of the waveguide is reduced and thus a compact circuit layout can be designed. In the previous section, the PBS with the double-pass MZI structure is integrated only for the signal, and not for the LO. On the other hand, in this section, we develop a PLC chip that integrates PBSs for both the signal and the LO, and 90-degree hybrid mixers.

First, Δ of the waveguide is optimised. Generally, a higher Δ makes the optical confinement of a guided mode stronger and the bending radius of the waveguide can then be reduced. Figure 6(a) shows the calculated minimum bending radius of the silica-based PLC for Δ. The minimum bending radius is monotonically decreased for an increased Δ. The relation between Δ and the thermal-expansion coefficient α of the SiO_2-GeO_2 glass is shown in Figure 6 (b), where α increases with Δ. In the range where Δ > 2.5%, α of the glass exceeds that of the silicon substrate. In this range, a tensile stress is induced in the glass and the reliability of the core glass is severely deteriorated. Furthermore, a highly doped GeO_2 for higher Δ, decreases the melting point of the core glass. As a result, the core shape is subject to deformation, and hence the fabrication repeatability becomes more difficult. For these reasons, a PLC with Δ higher than 2.5% is not realistic and Δ has to be carefully selected for practical use.

Here, we adopt 1.8% as an optimal value. With this value, the minimum bending radius is 1200 μm which is approximately a half of the conventional case, then the chip dimension can be more compact and enough reliability and repeatability in the fabrication process is guaranteed. In Figure 6, red points indicate Δ of 1.8%.

(a)



(b)

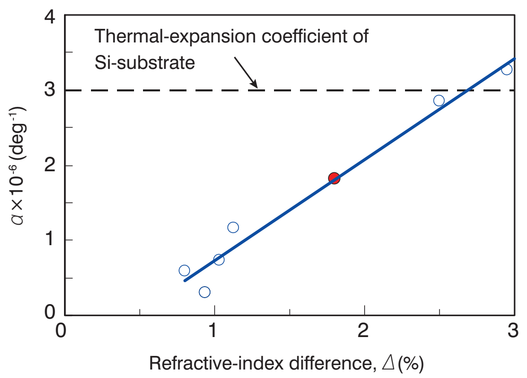
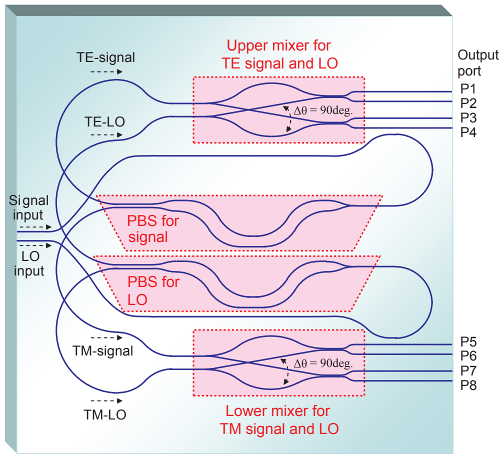


Figure 6 (a) A minimum bending radius and (b) a thermal-expansion coefficient of the silica-based PLC vs. Δ.

(a)



(b)

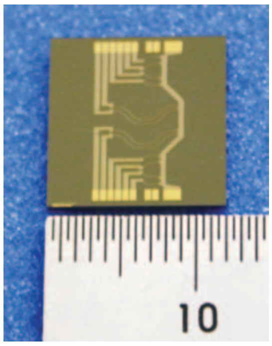


Figure 7 (a) The schematic diagram of the proposed circuit layout with a folded configuration, and (b) picture of the fabricated PLC-chip.

Second, a circuit layout to further reduce the dimension of a chip of PBS-integrated coherent mixer is studied. When two PBSs for the signal and the LO, and two 90-degree hybrid mixers for TE/TM polarization components are allocated straightforward along the direction parallel to the input and the output waveguides of the chip, the chip inevitably has a slender-rectangle shape in the longitudinal direction [10]. In this case, the circuit layout with a longitudinal length less than 15 mm is difficult even if the bending radius is reduced by increasing Δ. We then propose a folded configuration for a circuit layout shown in Figure 7 (a). By folding the waveguides at the input and output portions of the PBSs, the longitudinal dimension of the chip can be drastically reduced. We note here that there is no skew among any of the TE/TM components of the signal and the LO thanks to the symmetric structure of the four folded waveguides coming from the output of the two PBSs.

Based on the above considerations, we fabricated a PBS-integrated coherent mixer chip with the Δ of 1.8% and the circuit layout shown in Figure 7 (a). Figure 7 (b) depicts a picture of the fabricated chip, and the dimension is 12 mm×12 mm. The length on a side of the chip is less than 15 mm, which means the chip is enough small to be used in the OIF-compliant receiver front-end module.

The optical characteristics of the fabricated chip are shown as follows. Note that those characteristics are evaluated by connecting SMFs at both ends of the chip. Figure 8 shows the insertion loss. The insertion loss for each port is about 10 dB, which is estimated to comprise 6 dB for the intrinsic loss of a 90-degree hybrid, 2.2 dB for the connection loss between the PLC chip and the SMFs at both ends, and 1.8 dB for the excess circuit loss. Figure 9 shows the measurement results of the PER of the PBSs for the signal and the LO. For the both PBSs, the PER over 20 dB are obtained in the entire C-band (1530-1570 nm). Finally, Figure 10 (a) shows the intensity transfer functions in the frequency domain for MZIs comprising the integrated 90-degree hybrid mixers and an extra PLC chip similar to that used in the previous section. From the results, one can confirm that the integrated mixers work well as 90-degree hybrid. Figure 10 (b) shows the phase error of the 90-degree hybrid mixers calculated from the result of Figure 10 (a). The error is less than 5 degrees in absolute value, and the specification for OIF-compliant receiver front-end is then satisfied. In summary, the developed PLC chip has an ultra-small dimension and reasonable optical properties enough to be applied to an OIF-compliant receiver front-end module.

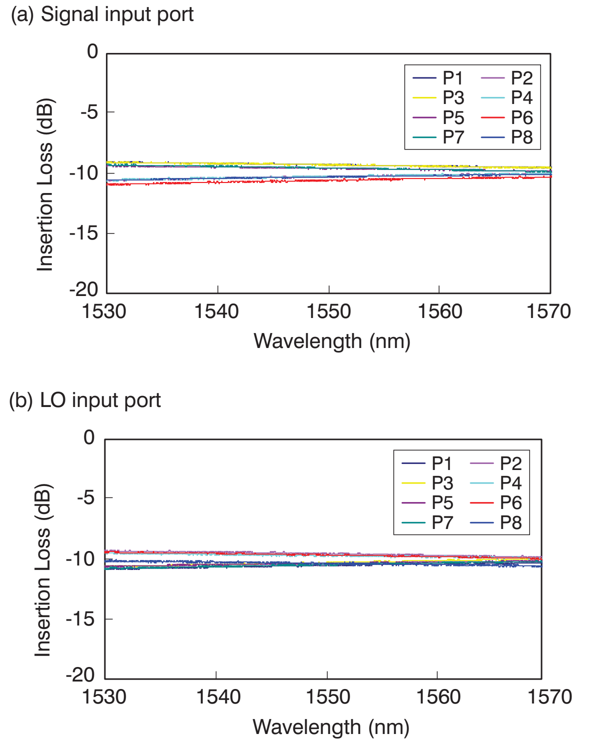


Figure 8 The insertion loss from input ports for (a) the signal and (b) the LO to output ports P1-P8.

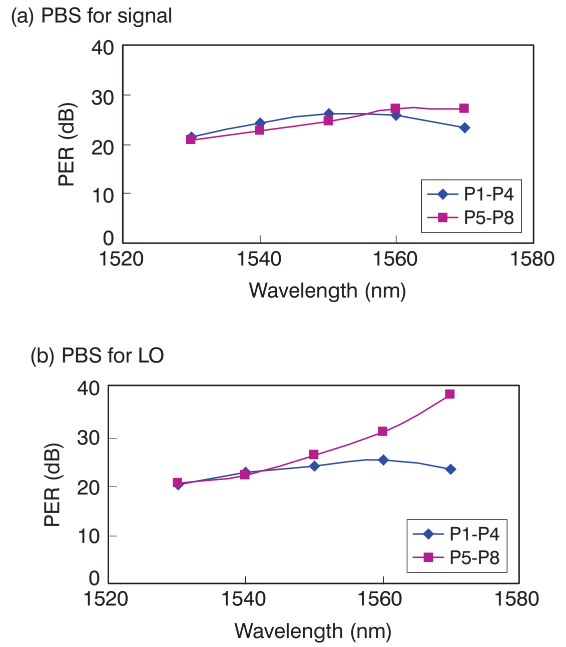


Figure 9 The polarization extinction ratio of PBSs for (a) the signal and (b) the LO.

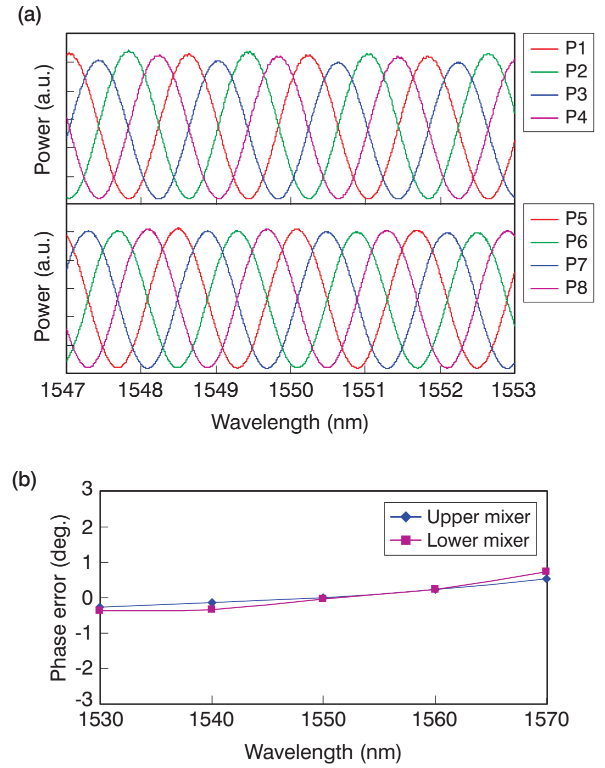


Figure 10 The phase characteristics for the upper and lower mixers in the chip
(a) The interference patterns in the vicinity of 1550 nm
(b) The phase error for the wavelength

A digital coherent receiver is built with the developed PLC chip, and evaluated by demodulating a 100-Gbit/s transmission signal with DP-QPSK format. Figure 11 shows the experimental setup. The wavelength of the optical signal and the LO is 1552 nm, and 100-km SMF is used for the transmission line. The developed PLC chip is used in the front end of the receiver, and the PLC and the BPDs are connected with the optical fibers.

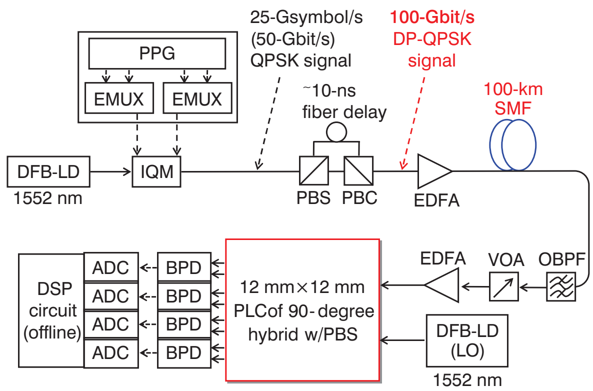


Figure 11 The setup for a 100-Gbit/s DP-QPSK signal transmission experiment.

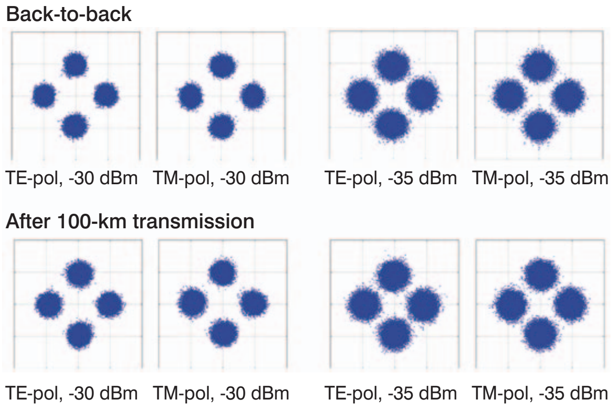


Figure 12 The constellation maps of a back-to-back (B-to-B) and a transmitted DP-QPSK signals.

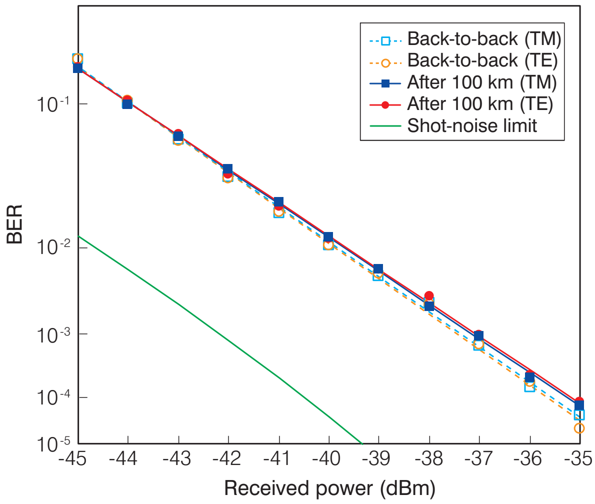


Figure 13 The BER characteristics of 100-Gbit/s DP-QPSK signals.

Figure 12 shows the constellation maps of DP-QPSK signals at back-to-back and after 100 km transmission, obtained after the digital coherent detection. Figure 12 shows the observation result of the clear constellation maps as a QPSK signal for the both TE/TM polarization components. Figure 13 shows the BER characteristics of the received signal. The BER is properly observed on a 100-Gbit/s DP-QPSK signal after a long distance transmission, which confirms that the developed PLC performs well as a component of the digital coherent receiver.

4. CONCLUSION

This paper illustrates the technical development results of a PBS-integrated coherent mixer using a silica-based planar lightwave circuit, which can be used in the digital coherent receiver front-end. The double-pass PBS-integrated coherent mixer realizes a polarization demultiplexing with the PER over 33 dB for the optical signal, and the satisfactory performance was confirmed in the transmission experiment to demodulate a 40-Gbit/s DP-QPSK signal. On the other hand, for downsizing of the chip size, Δ was increased to 1.8% and the minimum bending radius has been decreased. Furthermore, a folded waveguide configuration was adopted. Hence, an ultra-small PBS integrated coherent mixer chip with the dimension of 12 mm×12 mm was achieved. Satisfactory performance of this chip in a 100 Gbit/s DP-QPSK signal demodulation experiment was also confirmed.

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